Search for *CP* violation in $\tau \to K^0_S X$ and $D_{(s)} \to K^0_S X$ decays

Maurizio Martinelli[1,2]
on behalf of the *BABAR* Collaboration
Università degli Studi di Bari and INFN[1], SLAC[2]

May 26, 2011

FPCP 2011, Kibbutz Maale Hachamisha, Israel

CP Violation in τ decays

Bigi and Sanda, Phys. Lett. B 625, 47 (2005)

- The standard model predicts the transition amplitudes
$$T(\tau^- \to \overline{K}^0 \pi^- \nu) = T(\tau^+ \to K^0 \pi^+ \overline{\nu})$$
to be the same.

- Ignoring *CP* violation in $\Delta S \neq 0$ dynamics $\langle K_S | K_L \rangle = 0$
$$\Gamma(\tau^- \to \nu K_S^0 \pi^-) = \Gamma(\tau^- \to \nu K_L^0 \pi^-) = 0.5\Gamma(\tau^- \to \nu \overline{K}^0 \pi^-)$$
$$\Gamma(\tau^+ \to \overline{\nu} K_S^0 \pi^+) = \Gamma(\tau^+ \to \overline{\nu} K_L^0 \pi^+) = 0.5\Gamma(\tau^+ \to \overline{\nu} K^0 \pi^+)$$

- Including *CP* violation in $\Delta S = 2$ transitions $\langle K_S | K_L \rangle \neq 0$
$$\left|K_S^0\right\rangle = p\left|K^0\right\rangle + q\left|\overline{K}^0\right\rangle, \left|K_L^0\right\rangle = p\left|K^0\right\rangle - q\left|\overline{K}^0\right\rangle$$
$$\left\langle K_L^0 | K_S^0 \right\rangle = |p|^2 - |q|^2 \simeq 2\Re(\epsilon_K) \simeq (0.332 \pm 0.006)\%$$

from K^0_L CPV

and for short kaon decay times ($t_K \sim O(\Gamma_S^{-1})$)
$$\frac{\Gamma(\tau^+ \to [\pi^+\pi^-]_{K_S^0}\, \pi^+ \overline{\nu}) - \Gamma(\tau^- \to [\pi^+\pi^-]_{K_S^0}\, \pi^- \nu)}{\Gamma(\tau^+ \to [\pi^+\pi^-]_{K_S^0}\, \pi^+ \overline{\nu}) + \Gamma(\tau^- \to [\pi^+\pi^-]_{K_S^0}\, \pi^- \nu)} = |p|^2 - |q^2| = (-0.332 \pm 0.006)\%$$

New Physics in τ decays

Kühn and Mirkes, Phys. Lett. B 398, 407 (1997)
Weinberg, Phys. Rev. Lett. 37, 657 (1976)
Grossman, Nucl. Phys. B 426, 355 (1994)

- No *CPV* is expected in *SM* except for decays involving a K^0_S.
- In the Multi-Higgs-Doublet-Model a charged scalar boson $H^\pm$ can introduce a *CPV* in the angular distributions of the τ decays

$$F_S(Q^2) \to \widetilde{F}_S(Q^2) = F_S(Q^2) + \frac{\eta_S}{m_\tau} F_H(Q^2)$$

adimensional complex coupling constant

- The charged conjugate amplitude can be obtained substituting η_S with η_S^* and the *CP* violating quantity Δ_{LW} can be written as

from $d\Gamma_{\tau^-} - d\Gamma_{\tau^+}$

L_X=angular dependence; W_X=hadronic functions

$$\Delta_{LW} = \frac{1}{2}\left[\sum_X \bar{L}_X W_X(\eta_S) - \sum_X \bar{L}_X W_X(\eta_S^*)\right] = -4\frac{m_\tau}{\sqrt{Q^2}}|\vec{q}_1|\Im(FF_H^*)\Im(\eta_S)\cos\psi\cos\beta$$

$$\Delta_{LW} \propto \cos\psi\cos\beta \Rightarrow \int \Delta_{LW}\, d\psi d\beta = 0;\ \Delta_{LW} \neq 0 \Leftrightarrow \Im(FF_H^*) \neq 0$$

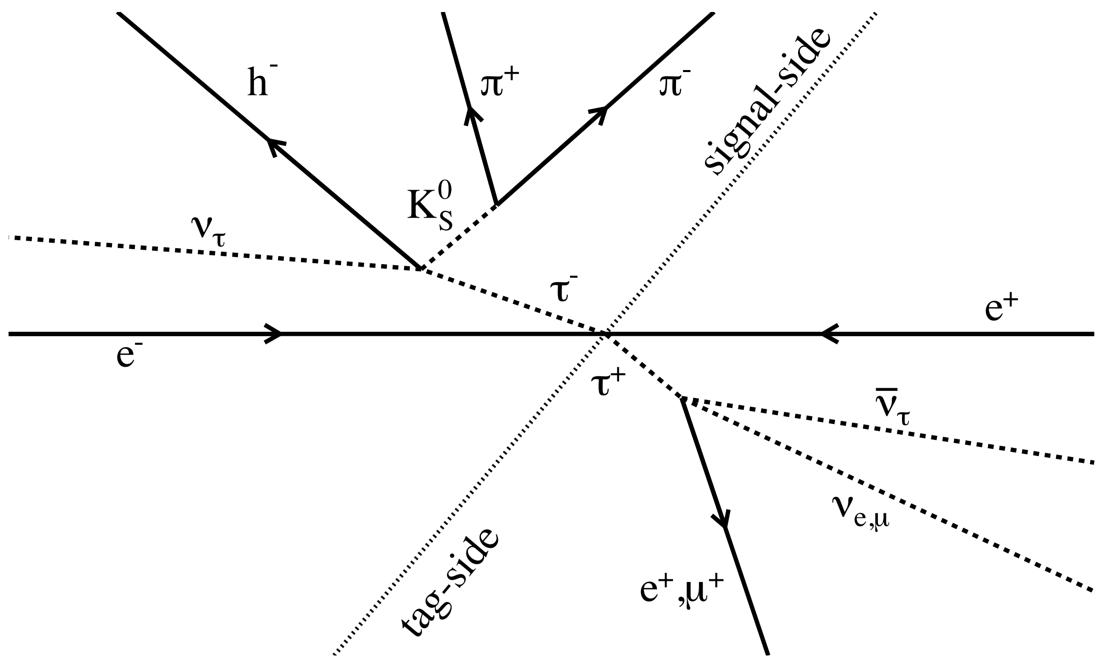
- *Im*(η_S) is the *CP* violating observable, and is related to A^{cp}

$$A^{cp} = \frac{\int \cos\beta\cos\psi\left(\frac{d\Gamma_{\tau^-}}{d\omega} - \frac{d\Gamma_{\tau^+}}{d\omega}\right)d\omega}{\frac{1}{2}\int\left(\frac{d\Gamma_{\tau^-}}{dQ^2} + \frac{d\Gamma_{\tau^+}}{dQ^2}\right)dQ^2} \simeq c_i \Im(\eta_S)$$

$d\omega = dQ^2 d\cos\theta d\cos\beta$

τ decays at B-factories

- Produced by $e^+e^-\to\tau^+\tau^-(\gamma)$ (0.92nb)
- At $\Upsilon(4S)$ they are jet-like.
- Detector split in tag-side and signal-side by the plane transverse to the thrust axis



- many analysis require a single prong (e,μ,π) in the tag-side hemisphere
- Backgrounds: (reduced by Mag(thrust)>0.9)
  - di-lepton with large radiation possibly undetected
  - low-multiplicity $q\bar{q}$ events
  - two-photon events

Search for CPV in $\tau^{\pm} \to K^0_S \pi^{\pm} \nu_\tau$

hep-ex/1101.0349v1

submitted to PRL

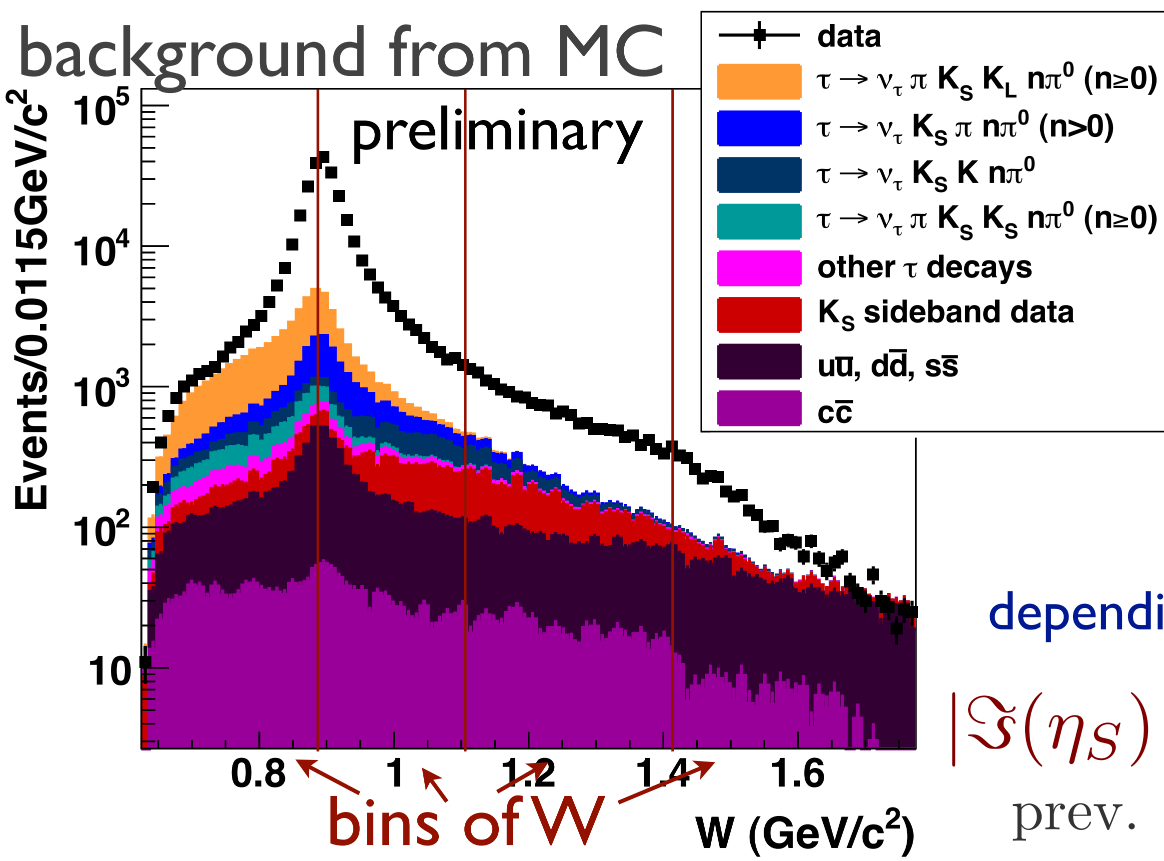
BELLE (699fb^{-1})

- Search for *CP* from *NP*: Measurement of A^{cp} in the partial wave amplitudes evaluated in 4 bins of $W=m(K^0_S\pi)$

$$A^{cp} \simeq \frac{\langle \cos\beta\cos\psi\rangle_{\tau^-}}{1-f_b^-} - \frac{\langle \cos\beta\cos\psi\rangle_{\tau^+}}{1-f_b^+}$$

$f_b^{\pm}$: background fraction for $\tau^{\pm}$

background from MC



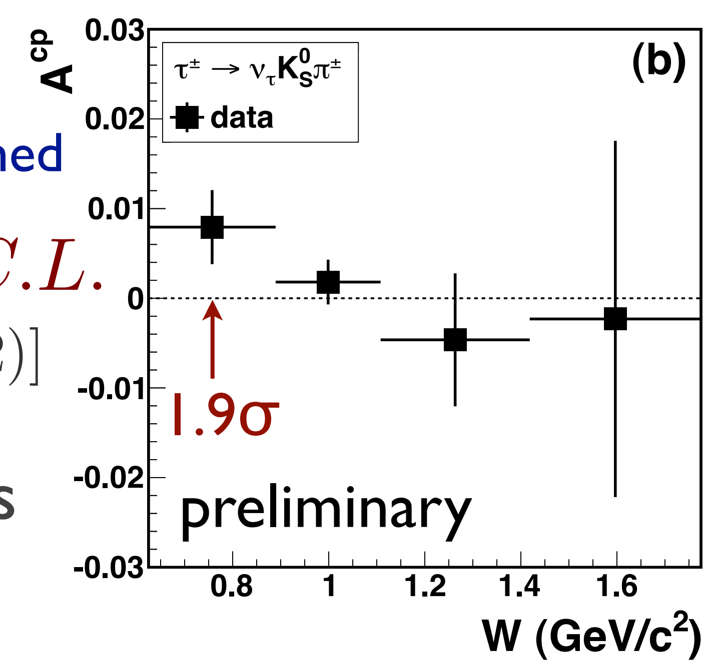
Systematic uncertainties (10^{-3}) in bins of W (GeV/c^2)	0.625 − 0.890	0.890 − 1.110	1.110 − 1.420	1.420 − 1.775
Detector	2.76	1.40	1.50	5.18
Backgr.	0.59	0.04	0.25	0.96
MC stat.	0.15	0.10	0.79	1.38
Total	2.83	1.40	1.71	5.45

A^{cp} consistent to 0

depending on strong interaction phase assigned

$$|\Im(\eta_S)| < (0.012 - 0.026)@90\%C.L.$$

prev. res.: $|\Im(\eta_S)| < 0.19$ [CLEO(2002)]



- The limit on $Im(\eta_S)$ has been evaluated for 3 parameterizations of F and F_S using $K^*(892)$, $K^*(1410)$, $K^*_0(800)$ and $K^*_0(1430)$.

CPV in *D* decays with a K^0_S

- Standard Model: *CP* violation from *KM* phase in *CKM* quark mixing matrix:

$$\begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta + \frac{i}{2}\eta\lambda^2) \\ -\lambda & 1-\frac{\lambda^2}{2} - i\eta A^2\lambda^4 & A\lambda^2(1+i\eta\lambda^2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

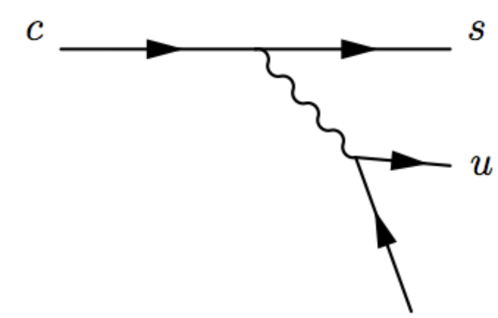
- Charmed Mesons:
  - *CP* violation is *CKM* suppressed $\mathcal{O}(10^{-3})$ or less
  - The presence of a K^0_S introduces *CPV* of (0.332±0.006)% from K^0/K^0_{bar} regeneration
  - Experimental Sensitivity $\mathcal{O}(10^{-3})$

1% Signal = New Physics

New Physics Scenario

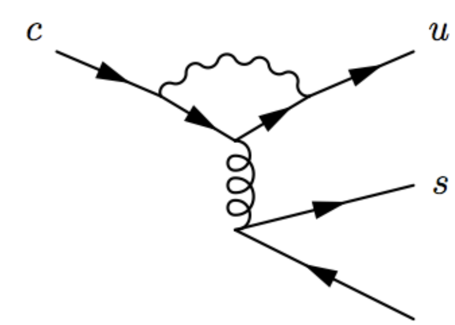
CPV ~ 1% Strong Evidence for non-*SM* processes

- Direct *CP* violation at tree level («1%)
  - extra quarks in *SM* vector-like representations
  - supersymmetry without *R*-parity models
  - two Higgs doublet models



(a) *Tree diagram.*

- Direct *CP* violation at one-loop (1%)
  - *QCD* penguin and dipole operators
  - *FCNCs* in supersymmetric flavor models.



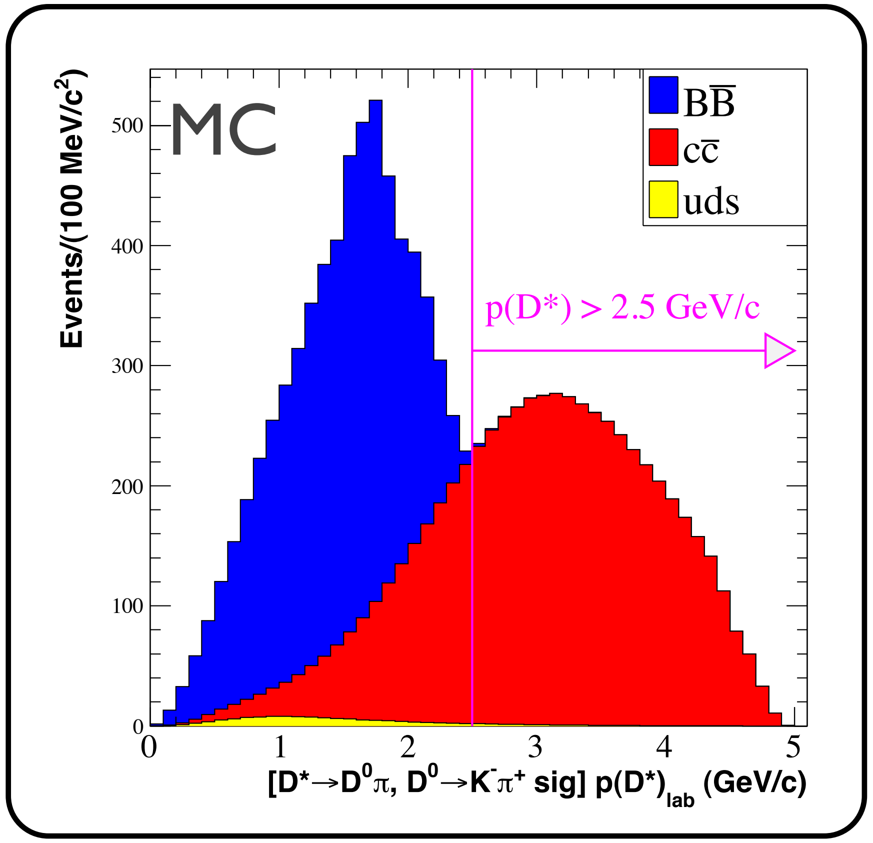
(b) *Penguin diagram.*

Singly Cabibbo Suppressed (*CS*) decays are uniquely sensitive to $c \rightarrow uq\bar{q}$ and are more likely to show the effect if present

Details:
Grossman, Kagan and Nir, Phys. Rev. D75, 036008 (2007)
Bigi, hep-ph/0104008 (2001)
Buccella et al., Phys. Rev. D51,3478 (1995)

Charm & *B*-factories

- Why search for *CP* violation at *B*-factories:
  - $\Upsilon(4S)\rightarrow c\bar{c}$, cross section = 1/4 total
  - require $p^{*}(D) > 2.5\ GeV/c$ to reduce background
  - $D^{*+}\rightarrow D^{0}\pi^{+}$ provides D^{0} flavor
  - Likelihood or *BDT* optimization when D^{*} not reconstructed



- Drawback: Electroweak Forward-Backward asymmetry

Direct *CP* violation

$$A_{CP}^{rec} = \frac{\Gamma_D - \Gamma_{\bar{D}}}{\Gamma_D + \Gamma_{\bar{D}}}$$

Γ = yields

- In asymmetric detectors like *BABAR* and *BELLE*, forward-backward asymmetry could bias these measurements
- *FB* asymmetry = *EW*+*EM* currents interference

$$N_c/N_{\bar{c}} = f(\cos\theta^*)$$

- We need to estimate *FB* asymmetry contribution A_{FB}
- Another source of asymmetry is the different interaction between particles of different charge and the detector A_ϵ
- The asymmetry measured is then

Need to quantify this part to retrieve A_{CP}

$$A_{CP}^{rec} = A_{CP} + \boxed{A_{FB} + A_\epsilon}$$

$D_{(s)}^+ \to K^0_S\pi^+$

BELLE ($673 fb^{-1}$)

Phys. Rev. Lett. 104, 181602 (2010)

$p^*(D) > 2.6 GeV/c$

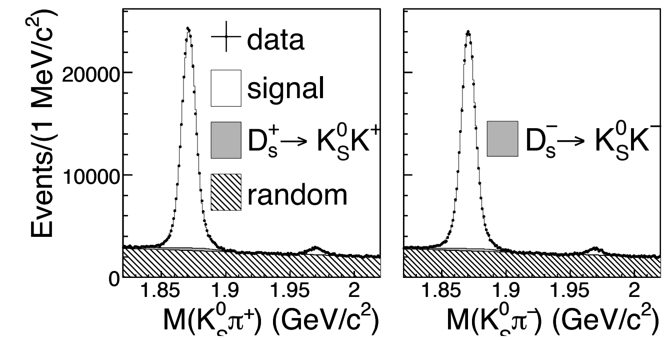
$A = |p_{KS} - p_\pi| / |p_{KS} + p_\pi| < 0.6$

$$A_{rec}^{D^+_{(s)} \to K^0_S \pi^+} = A_{CP} + A_{FB} + A_\epsilon^{\pi^+}$$

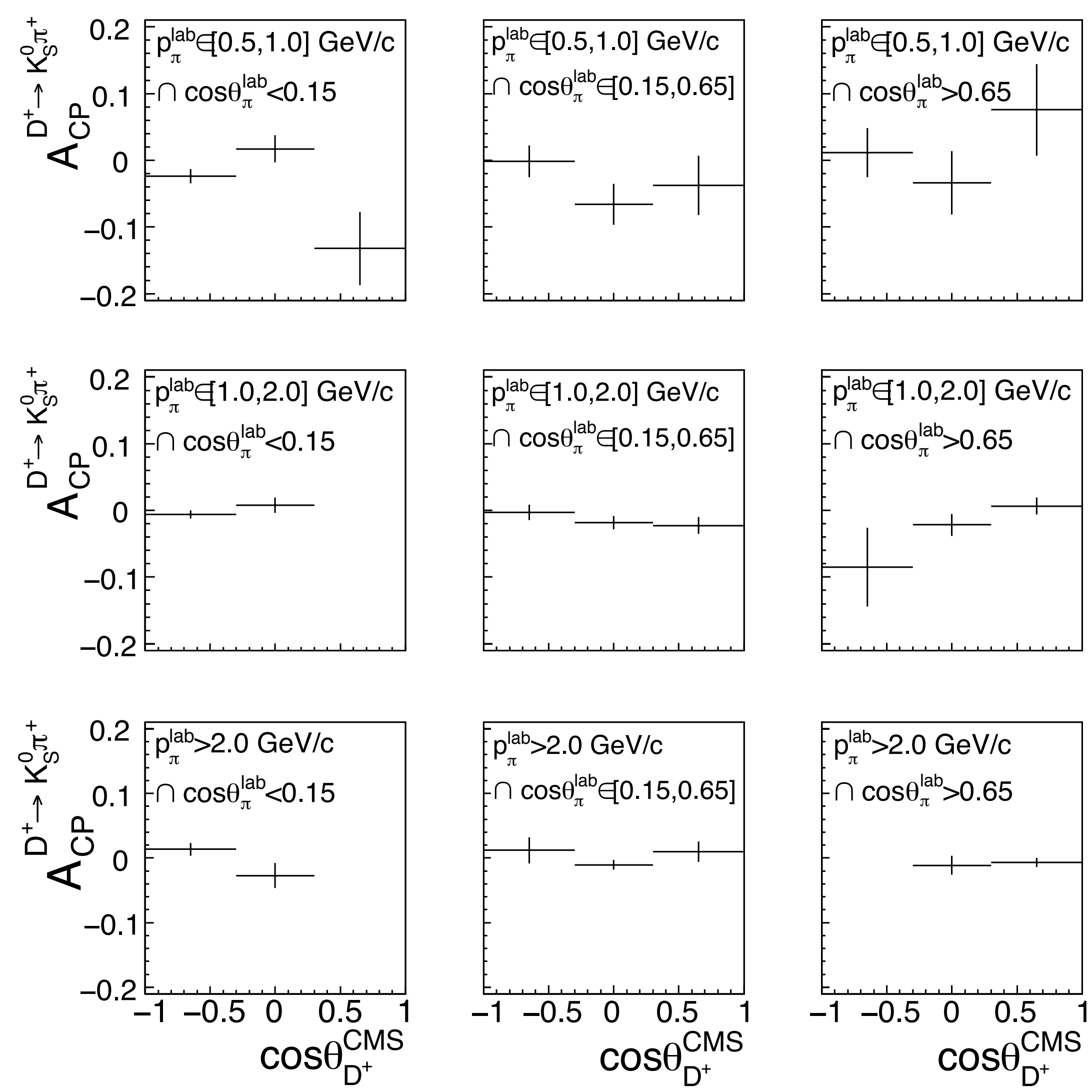
$D_s^+ \to \phi\pi^+$ control sample

CF: $A_{CP}=0$

$A_{FB}^{D^+} = A_{FB}^{Ds+}$



- Phase space divided in bins of p^{lab}_π, $\cos\theta^{lab}_\pi$, $\cos\theta^{CMS}_D$
- bin per bin subtraction
- A_{CP} obtained from weigthed mean for D^+
- A_{CP} from integrated phase space for D_s^+



systematics

	$\sigma_{syst}^{D^+ \to K^0_S\pi^+}$ (%)	$\sigma_{syst}^{D_s^+ \to K^0_S\pi^+}$ (%)
uncertainty on $A_{rec}^{D_s^+ \to \phi\pi^+}$	0.18	0.18
fit model	0.04	0.27
$K^0/\overline{K}^0$ interaction	0.06	0.06
total	0.20	0.33

final result:

$$A_{CP}^{D^+ \to K^0_S\pi^+} = (-0.71 \pm 0.26 \pm 0.20)\%$$

$$A_{CP}^{D_s^+ \to K^0_S\pi^+} = (+5.45 \pm 2.50 \pm 0.33)\%$$

SM

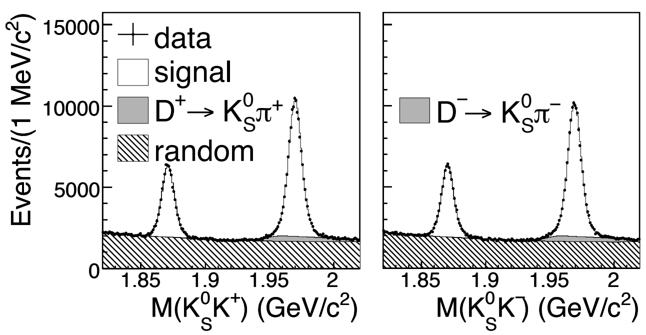
(-0.332)%

(+0.332)%

$D_{(s)}{}^{+} \to K^0{}_S K^+$

Phys. Rev. Lett. 104, 181602 (2010)

BELLE (673fb^{-1})



$$A_{rec}^{D_{(s)}^{+} \to K_S^0 K^+} = A_{CP} + A_{FB} + A_{\epsilon}^{K^+}$$

$$A_{\epsilon}^{K^-} = A_{rec}^{D^0 \to K^- \pi^+} - A_{rec}^{D_s^+ \to \phi \pi^+}$$

used to correct for $A_\epsilon{}^{K+}$

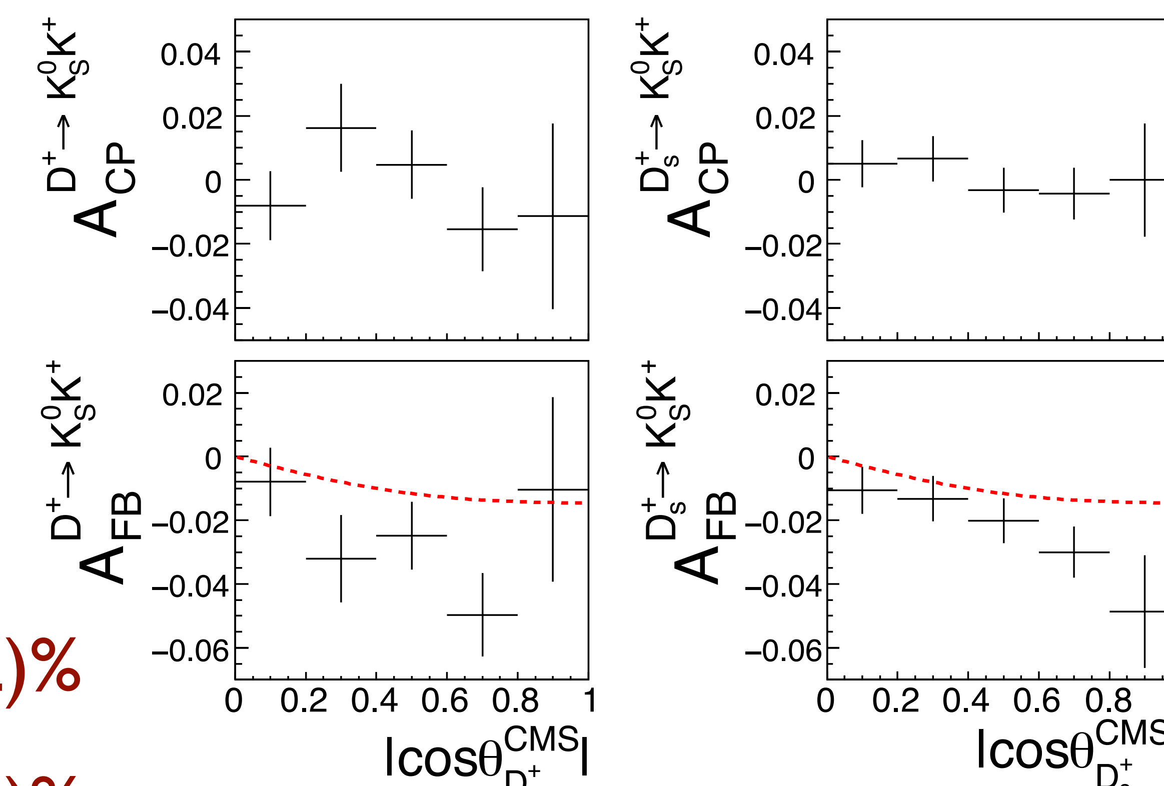
$$A_{CP}^{D_{(s)}^{+} \to K_S^0 K^+} = \frac{[A_{rec}^{corr}(\cos\theta_D^{CMS}) + A_{rec}^{corr}(-\cos\theta_D^{CMS})]}{2}$$

$$A_{FB}^{D_{(s)}^{+} \to K_S^0 K^+} = \frac{[A_{rec}^{corr}(\cos\theta_D^{CMS}) - A_{rec}^{corr}(-\cos\theta_D^{CMS})]}{2}$$

- A_{FB} odd on $\cos\theta^{CMS}{}_D$, while A_{CP} even:

systematics

	$\sigma_{syst}^{D^+ \to K_S^0 K^+}$ (%)	$\sigma_{syst}^{D_s^+ \to K_S^0 K^+}$ (%)
uncertainty on $A_\epsilon^{K^-}$	0.19	0.19
binning $\cos\theta_D^{CMS}$	0.06	0.06
fit model	0.12	0.05
$K^0/\overline{K}^0$ interaction	0.06	0.06
total	0.25	0.22



final result: SM

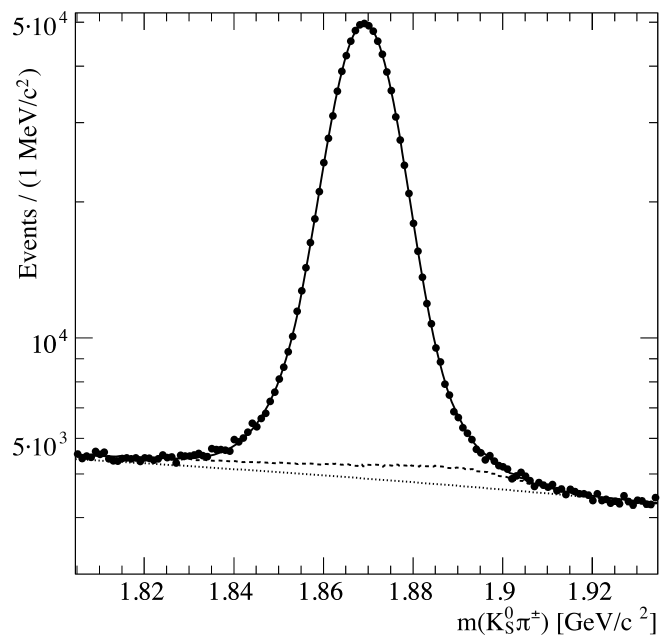
$$A_{CP}^{D^+ \to K_S^0 K^+} = (-0.16 \pm 0.58 \pm 0.25)\%$$ (-0.332)%

$$A_{CP}^{D_s^+ \to K_S^0 K^+} = (+0.12 \pm 0.36 \pm 0.22)\%$$ (-0.332)%

$D^+ \to K^0_S \pi^+$

Phys. Rev. D83, 071103(R) (2011)

BaBar (469fb^{-1})



- Signal optimization maximizing S/√(S+B) using *BDT* on *MC*: Vars: $\tau_T(D^\pm)$, $L_T(D^\pm)$, $p^*(D^\pm)$, $p(K^0_S)$, $p_T(K^0_S)$, $p(\pi^\pm)$, $p_T(\pi^\pm)$
- binned maximum likelihood fit: (807±1)x10^3 events

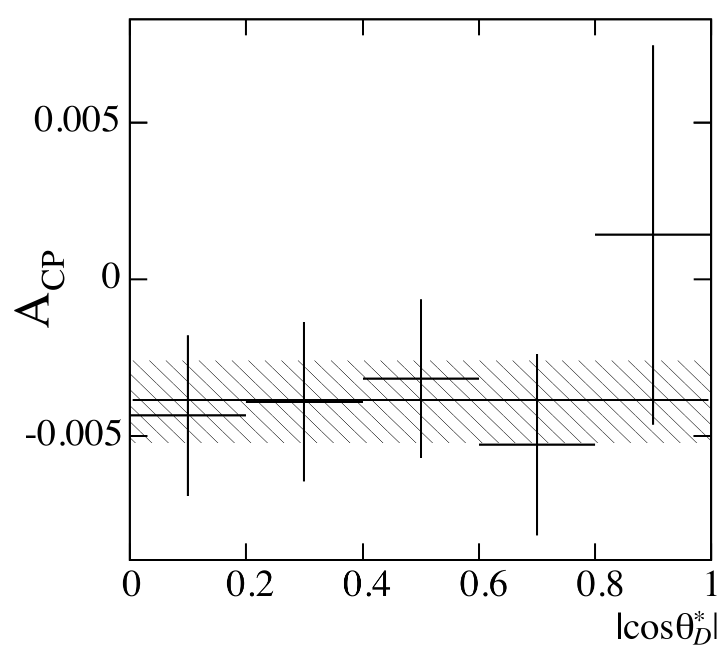
$$A = \frac{N_{D^+} - N_{D^-}}{N_{D^+} + N_{D^-}} = A_{CP} + A_{FB} + A^\pi_\epsilon$$

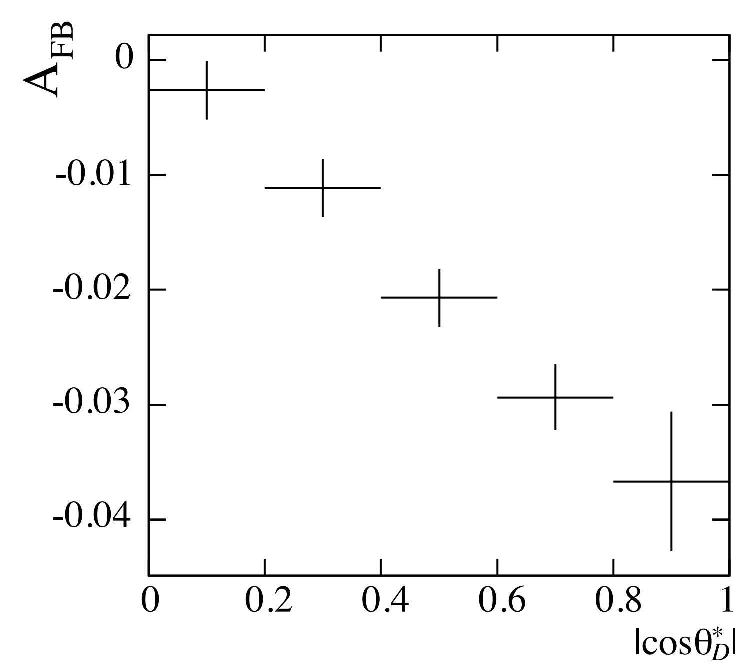
control sample of $B\bar{B}$ decays→efficiency map on $p(\pi)$ and $\theta(\pi)$ introduces a bias (+0.05)% in A_{CP}, included in systematics

$$A_{FB} = \frac{A(+|\cos\theta^*_D|) - A(-|\cos\theta^*_D|)}{2}$$

$$A_{CP} = \frac{A(+|\cos\theta^*_D|) + A(-|\cos\theta^*_D|)}{2}$$

A corrected for π efficiency weighting *D*$^-$ candidates





systematics

evaluation $A^{\pi^+}_\epsilon$	0.08%
$K^0/\overline{K}^0$ regeneration	0.06%
fit model	0.01%
total	0.10%

final result:

$$A_{CP} = (-0.44 \pm 0.13 \pm 0.10)\%$$

consistent to 0 (2.7σ) and to *SM* pred. (-0.332±0.006)%

$D^0 \to K^0_S P^0$ ($P=\pi,\eta,\eta'$)

Phys. Rev. Lett. 106, 211801 (2011)

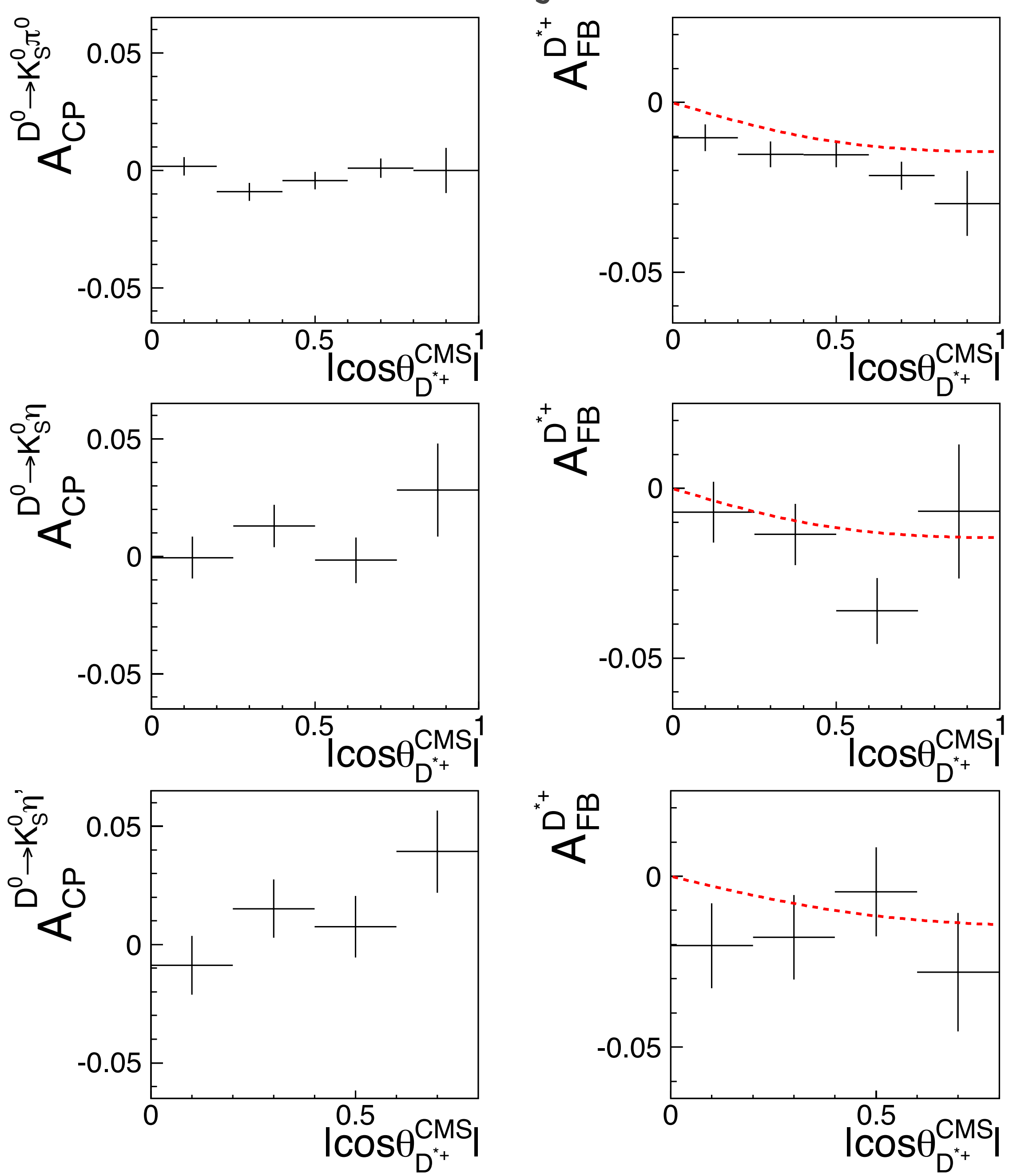
BELLE (791 fb^{-1})

- *SM* indirect *CPV* from mixing and interference (a^{ind})
- Reconstruction of $D^{*+} \to D^0 \pi^+_s$

$$A_{rec}^{D^{*+}\to D^0\pi_s^+} = \frac{N_{rec}^{D^{*+}} - N_{rec}^{D^{*-}}}{N_{rec}^{D^{*+}} + N_{rec}^{D^{*-}}} = A_{CP}^{D^{*+}\to D^0\pi_s^+} + A_{FB}^{D^{*+}} + A_\epsilon^{\pi_s^+}$$

from $D^0 \to K^- \pi^+$: $A_\epsilon^{\pi_s^+} = A_{rec}^{tagged} - A_{rec}^{untagged}$

- weights assigned to D^{*+} and D^{*-} depending on $p_T^{lab}(\pi_s)$ and $\cos\theta^{lab}(\pi_s)$ to correct for A_{rec}^{π}



systematics

Source	$K^0_S\ \pi^0$ (%)	$K^0_S\eta$(%)	$K^0_S\eta'$(%)
$A_\epsilon^{\pi^+}$ determination	0.08	0.08	0.08
signal extraction	0.02	0.12	0.10
A_{CP} extraction	< 0.01	0.01	0.03
$K^0/\overline{K}^0$ interaction	0.06	0.06	0.06
total	0.10	0.16	0.14

result:

$$A_{CP}^{D^0\to K^0_S\pi^0} = (-0.28 \pm 0.19 \pm 0.10)\%$$
$$A_{CP}^{D^0\to K^0_S\eta} = (+0.54 \pm 0.51 \pm 0.16)\%$$
$$A_{CP}^{D^0\to K^0_S\pi^0} = (+0.98 \pm 0.67 \pm 0.14)\%$$

test of indirect CP asymmetry (a^{ind}) universality:

$$a^{ind} = A_{CP}^{D^0\to K^0_S\pi^0} - A_{CP}^{K^0_S} = (+0.05 \pm 0.19 \pm 0.10)\%$$

consistent to $-A_\Gamma = (-0.01 \pm 0.30 \pm 0.15)\%$
from $D^0 \to h^+h^-(h=K,\pi)$

T-odd Correlations

W. Bensalem, A. Datta and D. London, Phys. Rev. D66, 094004 (2002)
W. Bensalem and D. London, Phys. Rev. D64, 116003 (2001)
W. Bensalem, A. Datta and D. London, Phys. Lett. B538, 309 (2002)

- Asymmetry in a T-odd observable→T violation→*CPV* (assuming *CPT* invariance)
- T-odd observable (v = spin or momentum)

$$A_T = \frac{\Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) > 0) - \Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) < 0)}{\Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) > 0) + \Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) < 0)}$$

← measured on D^+

- Final State Interactions (*FSI*) may fake the measurement producing $A_T \neq 0$
- To remove *FSI* effects

$$\mathcal{A}_T = \frac{1}{2}(A_T - \bar{A}_T)$$

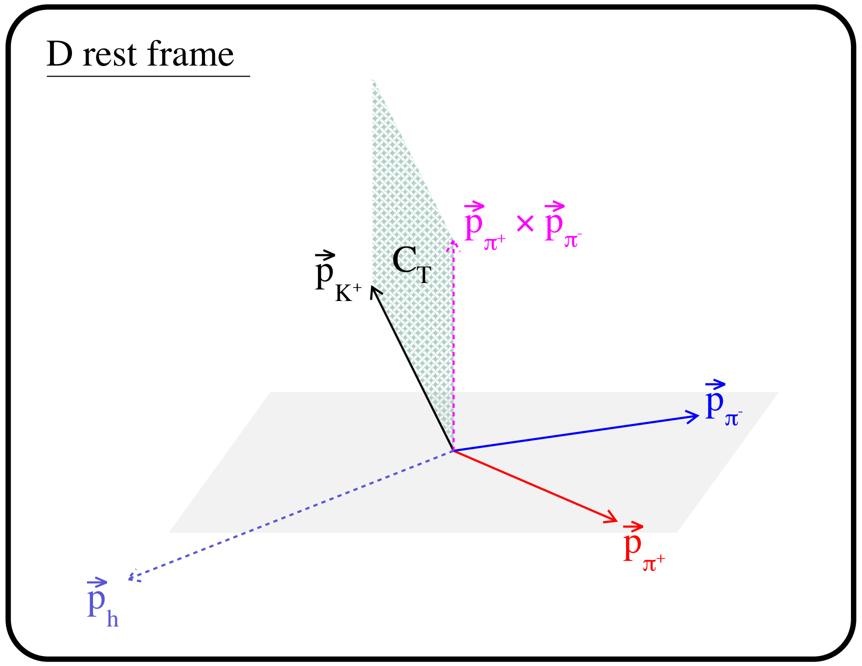
measured on D^- (→ $\bar{A}_T$)

T violation observable

- In $D_{(s)}^+ \to K^+ K^0_S \pi^+ \pi^-$

$$C_T = \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$$

T-odd observable

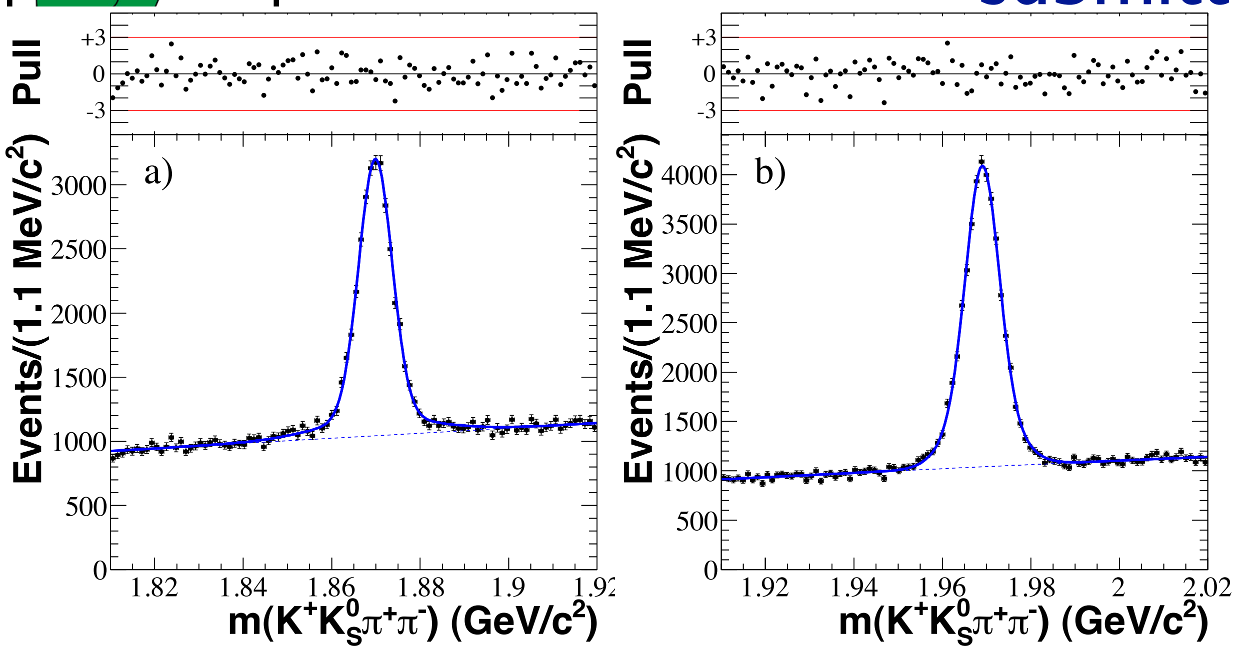


$D_{(s)}^+ \to K^+ K^0_S \pi^+ \pi^-$

hep-ex/1105.4410

submitted to PRD-RC

BABAR (520fb^{-1})



- Blind Analysis
- Inclusive $D_{(s)}^+$ reconstruction
- $p^*(D)>2.5$ GeV/c
- 20,000 D^+ and 30,000 D_s^+ decays

- Peaks optimized by means of likelihood ratio
- 3 variables: $p^*(D)$, P_1-P_2, $L_T(D)$

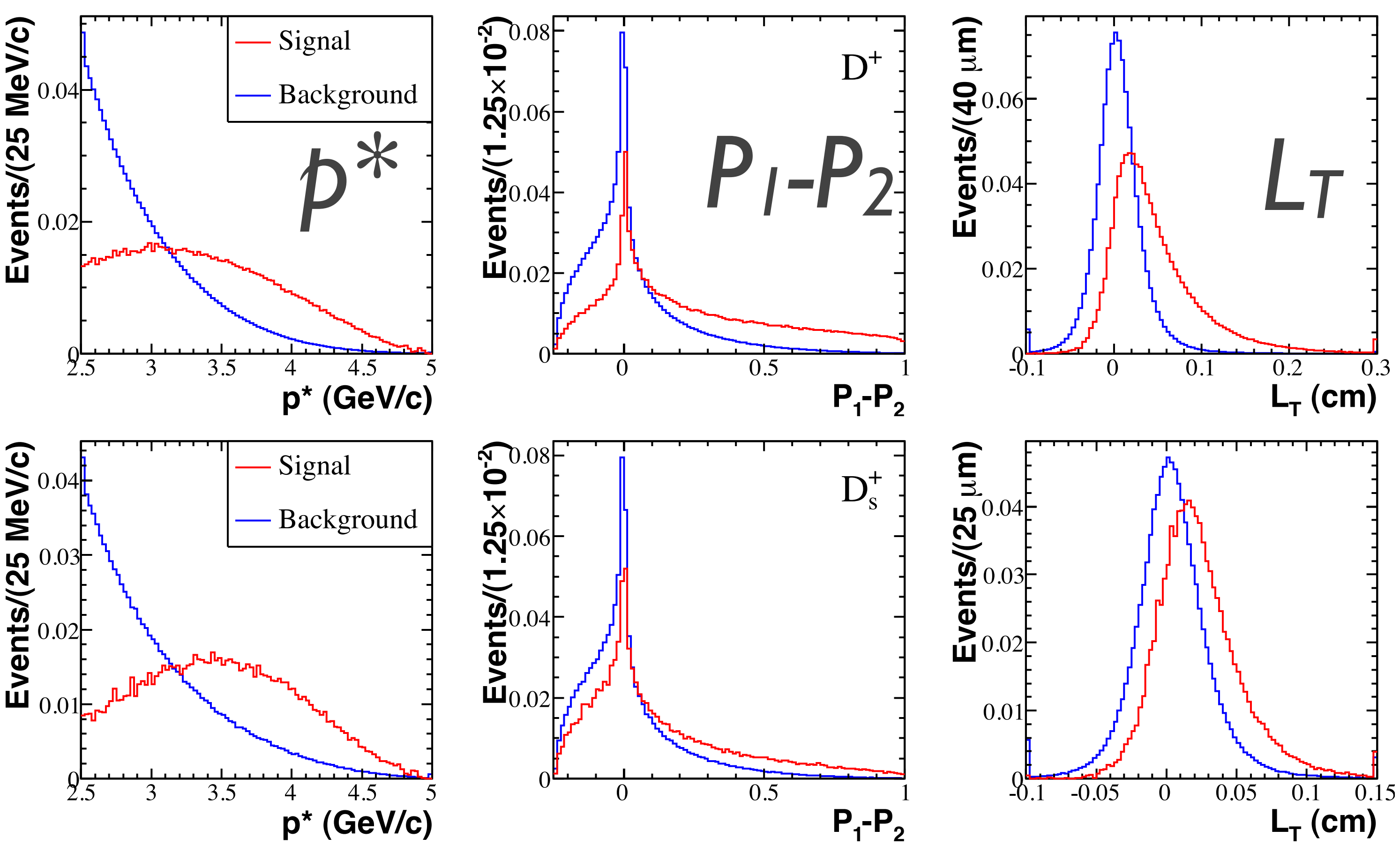
  P_1=nominal fit probability

  P_2=fit probability constraining D vtx to IR

  $L_T(D)$=transverse D decay length
- signal distributions from

  $D^+ \to K^0_S \pi^+ \pi^+ \pi^-$

  $D_s^+ \to K^- K^0_S \pi^+ \pi^+$
- background from data sidebands

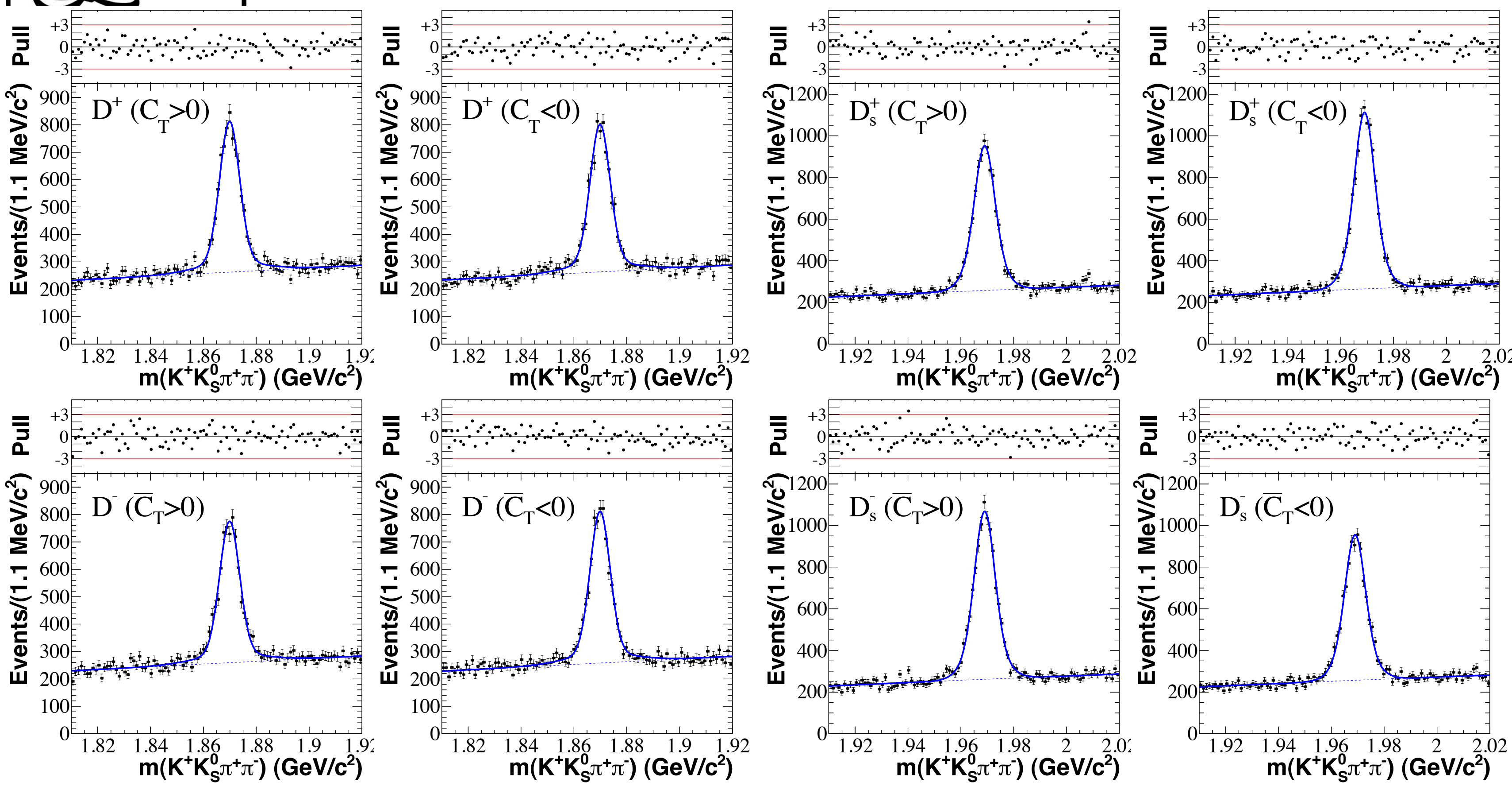


$D_{(s)}^+ \to K^+ K^0_S \pi^+ \pi^-$ cont.

hep-ex/1105.4410

submitted to PRD-RC

BABAR ($520 fb^{-1}$)



- Dataset split depending on $D_{(s)}$ charge and C_T value
- Simultaneous binned maximum likelihood fit
- Peak: 2 Gaussians with common mean
  Background: line(D^+), 2nd order polynomial (D_s^+)

systematics

x 10^{-3}

Effect	$\mathcal{A}_T(D^+)$	$A_T(D^+)$	$\bar{A}_T(D^-)$	$\mathcal{A}_T(D_s^+)$	$A_T(D_s^+)$	$\bar{A}_T(D_s^-)$
1) Reconstruction	2.05	2.84	1.26	1.00	1.00	1.27
2) Likelihood Ratio	1.08	3.41	5.58	2.46	7.77	8.16
3) Fit Model	1.30	1.14	1.46	0.10	0.78	0.70
4) Particle Identification	3.70	3.33	4.08	2.22	2.47	6.73
Total	4.56	5.66	7.18	3.43	8.25	10.67

$D_{(s)}^+ \to K^+K^0_S\pi^+\pi^-$ cont.

hep-ex/1105.4410

submitted to PRD-RC

BABAR ($520 fb^{-1}$)

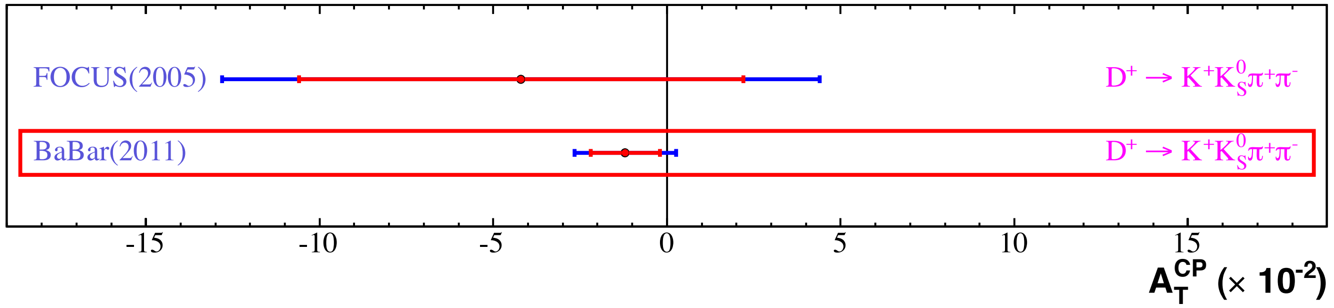
- Final Results

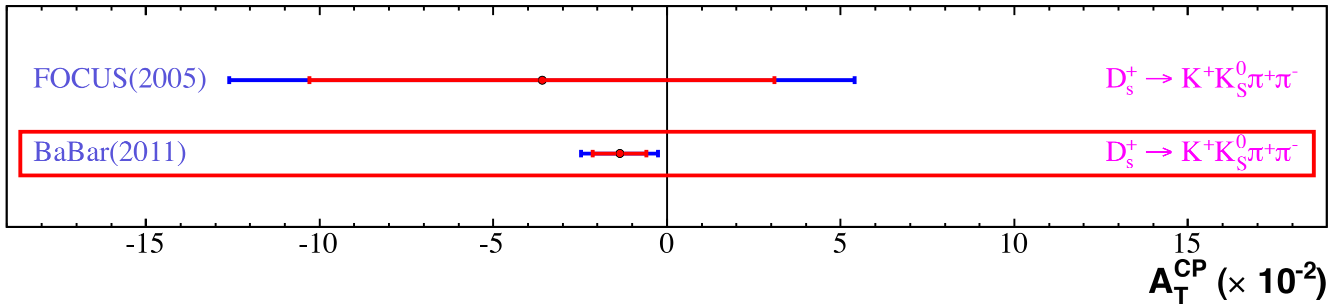
$$A_T(D^+) = (+11.2 \pm 14.1_{\rm stat} \pm 5.7_{\rm syst}) \times 10^{-3}$$
$$\bar{A}_T(D^-) = (+35.1 \pm 14.3_{\rm stat} \pm 7.2_{\rm syst}) \times 10^{-3}$$
$$A_T(D_s^+) = (-99.2 \pm 10.7_{\rm stat} \pm 8.3_{\rm syst}) \times 10^{-3}$$
$$\bar{A}_T(D_s^-) = (-72.1 \pm 10.9_{\rm stat} \pm 10.7_{\rm syst}) \times 10^{-3}$$

Final state interaction effects seem to be larger in D_s^+ than D^+ decays

$$\mathcal{A}_T(D^+) = (-12.0 \pm 10.0_{\rm stat} \pm 4.6_{\rm syst}) \times 10^{-3}$$
$$\mathcal{A}_T(D_s^+) = (-13.6 \pm 7.7_{\rm stat} \pm 3.4_{\rm syst}) \times 10^{-3}$$

T violation parameter consistent to 0.
Factor 10 better than previous result.





Conclusions

- The search for *CP* violation in the charm sector has explored many channels and different approaches.
- In the last years a vivid interest on this topic resulted into the publication of many new results.
- We have reached the limit of the *B*-factories, obtaining sensitivities of 10^{-3}, but the *CP* violation from $c \rightarrow s$ transition didn't show up yet, neither from *SM* or *NP*.
- The new high-luminosity machines can light on this topic, providing new limits for *CP* violation in charm decays or even a measurement.
- We then strongly suggest to perform similar analysis at *LHCb* and to include them in the physics program of the next high-luminosity *B*-factories (*SuperB* and *Super KEK-B*).